

EXPLORING LEPTONIC CP VIOLATION WITH COMBINED ANALYSIS OF REACTOR AND NEUTRINO SUPERBEAM EXPERIMENTS

HIROAKI SUGIYAMA

Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan

E-mail: hiroaki at post.kek.jp

We investigate the possibility to find the leptonic CP-violation by combining the reactor experiment with the superbeam experiment without antineutrino superbeam. We show also how much the sensitivity on CP-violating phase δ is affected by the fact that we have not known the sign of Δm_{31}^2 .

1 Introduction

Observing the leptonic CP-violation is one of aims in future experiments of the neutrino oscillation. It can be achieved by comparing oscillation probabilities with neutrino beam and its antiparticle one; For example, T2K experiment will measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ precisely in its phase II. Such a comparison is important obviously because it gives a direct observation of the leptonic CP-violation (except the matter effect mimics the CP-violation). It seems, however, the matter of the simple method that the exposure with antineutrino beam needs to be about three times longer than that with neutrino beam because of its smaller detection cross-section; In phase II of T2K experiment, about 6year exposure with $\bar{\nu}_\mu$ is planed after 2year exposure with ν_μ beam. The smaller cross-section even gives worth S/N ratio. Thus, it seems fruitful to consider other possibilities to see CP-violation.

In the scheme of three neutrino oscillation, the CP-violation is controlled by the CP-violating phase δ . If we can know δ is not vanishing, it means a measurement of CP-violation indirectly by assuming three neutrino oscillation. The information about δ is included in $P(\nu_\mu \rightarrow \nu_e)$, but the oscillation probability include θ_{13} also as the parameter to be determined. That is why we require additionally the measurement of $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, whose parameters to be determined are also δ and θ_{13} , to extract the value of δ . Any

oscillation probability, however, can be the additional one as long as it has information on the value of θ_{13} . In this talk¹, we consider a combination of a superbeam experiment with neutrino beam and a reactor experiment, which is a pure measurement of θ_{13} , to explore the CP-violation in lepton sector. Note that the method have an advantage of speed because the reactor experiment can run parallel to the superbeam ν experiment in contrast with the superbeam $\bar{\nu}$ experiment. Although we can extract the value of δ from the combination of reactor and superbeam ν experiments in principle, a quantitative analysis is necessary for concreteness.

2 Settings

As a superbeam experiment, we deal with phase II of T2K experiment without $\bar{\nu}_\mu$ beam; The beam power is assumed to be 4MW, the fiducial volume of detector (Hyper-Kamiokande) is 540kt, and the exposure time is 2 years with off-axis 2deg. ν_μ beam. Total number of events within 0.4-1.2GeV is used for the analysis, and we assume 2% systematic errors for estimations of numbers of signal and background events: $\sigma_S = \sigma_{BG} = 2\%$. Throughout this talk, oscillation parameter values are fixed as follows: $|\Delta m_{31}^2| = 2.5 \times 10^{-3} \text{eV}^2$, $\Delta m_{21}^2 = 7.3 \times 10^{-5} \text{eV}^2$, $\tan^2 \theta_{12} = 0.38$ (32°), $\sin^2 2\theta_{23} = 1$ (90°). Earth matter density is chosen as $\rho = 2.3 \text{g} \cdot \text{cm}^{-3}$.

On the other hand, we deal with a simple complex of one reactor and two detectors

		between detectors		single detector
		correlated	uncorrelated	
between bins	correlated	$\sigma_{DB} = 2.5\%$	$\sigma_{dB} = 0.5\%$	$\sigma_B \simeq 2.6\%$
	uncorrelated	$\sigma_{Db} = 2.5\%$	$\sigma_{db} = 0.5\%$	$\sigma_b \simeq 2.6\%$
total number of events		$\sigma_D \simeq 2.6\%$	$\sigma_d \simeq 0.5\%$	$\sigma_{\text{sys}} \simeq 2.7\%$

Table 1. Listed are assumed values of systematic errors σ_{DB} , σ_{Db} , σ_{dB} , and σ_{db} . The subscripts D (d) and B (b) are represent the correlated (uncorrelated) error among detectors and bins, respectively. Using those four values, the errors for the total number of events and for single detector are calculated. (See Appendix.) $\sigma_d \simeq 0.5\%$ means 0.8% relative normalization error on the comparison of numbers of events at near and far detectors: $0.8\% \simeq \sqrt{2}\sigma_d$. $\sigma_{\text{sys}} = 2.7\%$ corresponds to the systematic error in CHOOZ experiment.

as a future reactor experiment. The simple set-up is a good approximation if the set-up of the future reactor experiment is appropriate enough. Since the determination of δ requires very precise measurement, the position of the far detector is assumed to be optimal one which is 1.7km away from the reactor and the scale of the reactor experiment is assumed to be rather large, $\sim 10^3 \text{GW}_{\text{th}} \cdot \text{ton} \cdot \text{year}$ ('thermal power of the reactor' times 'detector volume' times 'exposure time'). $\overline{\nu}_e$ detection efficiency is assumed to be 70%. Furthermore, we rely upon spectral information also for the precise determination of θ_{13} . We use 14 bins of 0.5MeV width in 1-8MeV visible energy: $E_{\text{visi}} = E_{\overline{\nu}_e} - 0.8\text{MeV}$. For the analysis, four types of systematic errors (σ_{DB} , σ_{Db} , σ_{dB} , σ_{db}) should be considered at least. An example of σ_{DB} is the error in reactor power, which gives a common effect on numbers of events in all bins at each detector. σ_{Db} is, for example, the error in energy dependence (shape) of flux or cross-section, which is bin-by-bin uncorrelated but correlated between detectors. A typical origin of σ_{dB} is the error in detector volume, which has overall effect for all bins but is uncorrelated between detectors. σ_{db} is completely-uncorrelated error and somewhat accidental one; Such a error dominates the sensitivity because it can not be cancelled by any comparison (detectors, bins). Assumed values of those errors are listed in Table 1. Note that if σ_{db} is set to be zero, the sensitivity does

not saturate even for extremely long exposure and then unrealistically high sensitivity is obtained.

3 Reactor-superbeam combined analysis

Fig. 1 shows how the combined analysis works; Best-fit values of θ_{13} and δ , which are chosen by nature, are assumed to be $\sin^2 2\theta_{13}^{\text{best}} = 0.08$ and $\delta^{\text{best}} = \pi/2$ in Fig. 1, respectively. Fig. 1(a) shows an allowed region that we obtain when $P(\nu_\mu \rightarrow \nu_e)$ is measured in T2K phase II. The allowed region depends on δ through Jarlskog factor. On the other hand, the reactor experiment gives another allowed region as is shown in Fig. 1(b). The allowed region is independent of δ because the reactor experiment is a pure measurement of θ_{13} . Roughly speaking, the overlap between those two allowed regions results in the allowed region obtained by the combined analysis. Fig. 1(c) shows the actual result obtained by the combined analysis for the input values of θ_{13} and δ . Since $\delta = 0$ is excluded by the combined analysis in this case, we find that CP is violating in the lepton sector. Then, we want to know which values of $\theta_{13}^{\text{best}}$ and δ^{best} exclude the hypothesis $\delta = 0$ by the combined analysis.

Fig. 2 shows the regions that are consistent with the hypothesis $\delta = 0$ at 90%CL. Therefore, we find that CP is violating, if nature chooses the values of $\theta_{13}^{\text{best}}$ and δ^{best} outside of the envelope of those regions. If

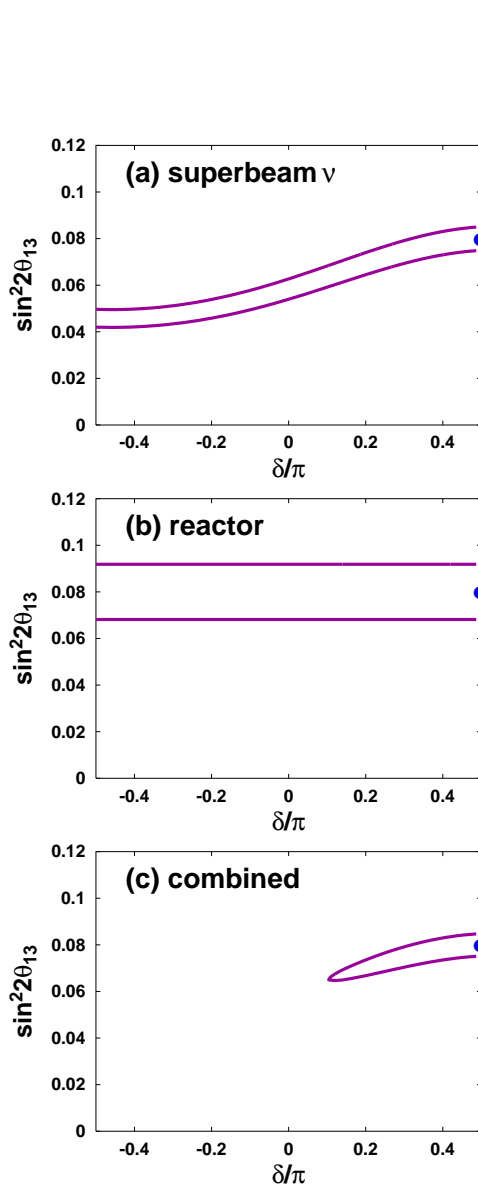


Figure 1. The true values are assumed to be $\sin^2 2\theta_{13}^{\text{best}} = 0.08$ and $\delta^{\text{best}} = \pi/2$ as an example. (a) shows the allowed region for a given $P(\nu_\mu \rightarrow \nu_e)$ to be obtained in the superbeam experiment. The allowed region to be obtained by reactor experiment is presented in (b). (c) is the result of the combined analysis.

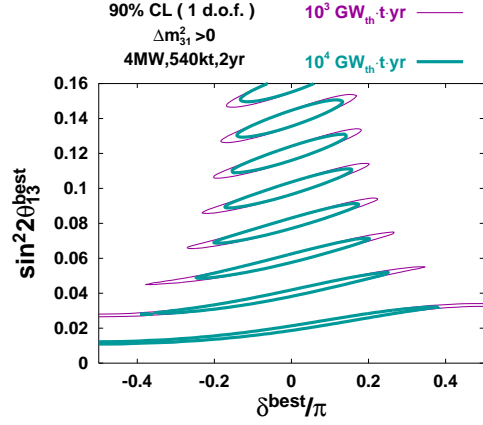


Figure 2. Shown are the regions consistent with the hypothesis $\delta = 0$ at 90%CL by the reactor-superbeam combined analysis. Thin and bold lines are for 10^3 and $10^4 \text{ GW}_{\text{th}} \cdot \text{ton} \cdot \text{year}$ exposure of the reactor experiment. If nature chooses outside of those regions, we know CP is violating.

δ^{best} is very close to $\delta = 0$, we can not distinguish them. If $\theta_{13}^{\text{best}}$ is too small, δ is not so much restricted by the combined analysis because of small Jarlskog factor, namely small δ -dependence of the allowed region obtained by T2K phase II with ν_μ beam. Fig. 2 is consistent with those qualitative expectation. We see in Fig. 2 that we can find leptonic CP-violation at 90%CL if $\sin^2 2\theta_{13}^{\text{best}} \geq 0.05$ (6°) and $\delta^{\text{best}} \geq 0.3\pi$ (54°).

Actually, we fixed the sign of Δm_{31}^2 as positive in Fig. 2. The sign has, however, not been determined yet. Thus, we must use each sign of Δm_{31}^2 for fitting even if nature chooses positive value because we do not know the nature's choice. Fig. 3 shows the result for the case of unknown sign of Δm_{31}^2 . If the sign of Δm_{31}^2 is known, we can use solid lines only. Then, for example, we find CP is violating if nature chooses the values indicated by circle or cross in Fig.3. For the case of unknown sign of Δm_{31}^2 , we must use dashed lines also, and the point of cross mark enters their region. It means that even though nature chooses $\delta^{\text{best}} = \pi/2$ (maximal CP-

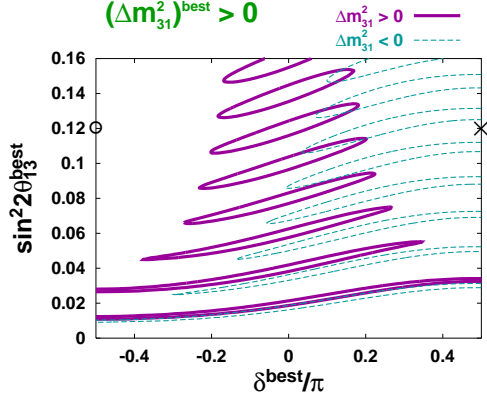


Figure 3. The contours are regions consistent with $\delta = 0$. The true sign of Δm^2_{31} is assumed as $(\Delta m^2_{31})^{\text{best}} > 0$. Solid lines are for fitting with $\Delta m^2_{31} > 0$, and dashed-lines are for fitting with $\Delta m^2_{31} < 0$.

violation), it can be explained by $\delta = 0$ with wrong sign of Δm^2_{31} . Roughly speaking, almost a half of sensitivity region is contaminated by the fitting with wrong sign of Δm^2_{31} . Since it is caused by $P(\nu_\mu \rightarrow \nu_e)$, the contamination occurs even for the conventional method with antineutrino superbeam.

4 Conclusions

In this talk, we considered determining leptonic CP-violation by using combined analysis of reactor and superbeam experiments with neutrino beam. We found that it is possible with the method to know that CP-violating phase δ is not vanishing at 90%CL if nature chooses $\sin^2 2\theta_{13}^{\text{best}} \geq 0.05$ and $\delta^{\text{best}} \geq 0.3\pi$ (54°) as the true values. Actually, the sensitivity is worse than that of conventional method (99.73%CL determination for $\sin^2 2\theta_{13}^{\text{best}} \geq 0.02$ and $\delta^{\text{best}} \geq 20^\circ$) in which superbeam ν experiment is combined with subsequent long-term experiment of $\bar{\nu}$ superbeam. The reactor-superbeam combined method, however, can give earlier information on δ because the reactor experiment can

start before the finish of superbeam ν experiment. Such a information will be helpful for later precise measurement of δ with conventional method. Therefore, the new combined method seems to be worth doing.

We should keep in our mind that unknown sign of Δm^2_{31} makes the sensitivity on δ worse very much even with rather short baseline experiment such as T2K (295km). It is the problem not only for reactor-superbeam combined method but also for conventional method.

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Appendix

The following is how to calculate σ_B , σ_b , σ_D , σ_d , and σ_{sys} from σ_{DB} , σ_{Db} , σ_{dB} , and σ_{db} .

$$\sigma_B^2 = \sigma_{\text{DB}}^2 + \sigma_{\text{dB}}^2, \quad \sigma_b^2 = \sigma_{\text{Db}}^2 + \sigma_{\text{db}}^2,$$

$$\sigma_D^2 = \sigma_{\text{DB}}^2 + \sigma_{\text{Db}}^2 \frac{\sum_i (N_{ni}^{\text{best}})^2}{(\sum_i N_{ni}^{\text{best}})^2},$$

$$\sigma_d^2 = \sigma_{\text{dB}}^2 + \sigma_{\text{db}}^2 \frac{\sum_i (N_{ni}^{\text{best}})^2}{(\sum_i N_{ni}^{\text{best}})^2},$$

$$\sigma_{\text{sys}}^2 = \sigma_D^2 + \sigma_d^2 = \sigma_B^2 + \sigma_b^2 \frac{\sum_i (N_{ni}^{\text{best}})^2}{(\sum_i N_{ni}^{\text{best}})^2}.$$

N_{ni}^{best} denotes the number of signal events within i th bin at near detector, which calculated for best-fit (input) values of parameters as an “experimental data”. In our analysis, the coefficient of σ_{Db}^2 is about 1/9.

References

1. H. Minakata and H. Sugiyama, Phys. Lett. B **580**, 216 (2004) [arXiv:hep-ph/0309323]. See also the references therein.